Constraining new physics with high-multiplicity: UHECR as a probe of new physics

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July 5th, 2018 @ COEX, Seoul
36th ICHEP2018

• No New physics has been found at the LHC

\[ \Lambda_{NP} \geq \text{TeV} \]

• We can go beyond the collider energy using UHECR

\[ E_{\text{CR}} > 10^8 \text{GeV} \Rightarrow E_{CM} = \sqrt{2E_{CR}M} > 10 \text{ TeV} \]

• So, we may probe new physics appearing at high scale by CR!

\[ E_{CM} > \Lambda_{NP} \]
Seen in atmosphere!

- CR $> 10^8$ GeV fiercely bombing the Earth
- They interact with nucleons in atmosphere
- Producing multiple ‘high-multiplicity events’
- That may be seen at the ‘detectors’ … TA, Pierre Auger are our main target in this study. (IceCube will come as a sequel soon)
What new physics?

\[ \Lambda_{NP} \sim 10 \text{ TeV} \]

- We don’t know actually where NP would show up but…
  
  - ‘Electroweak sphaleron’ scale \(~10 \text{ TeV}\) (a classical field configuration of SU(2) symmetry linking different vacuum states within the SM)
  
  - Microscopic blackhole is a robust prediction of low-scale gravity scenarios with warped or large extra dimensions, \(~10 \text{ TeV}\)
Sphaleron process

\[ \Delta L = -3, \Delta B = -3 \]

\[ N(u) + \nu_e \rightarrow L + Q \quad (+\text{EW bosons}) \]

UHECR Neutrino

\[ E_{\text{sph}} \approx 10\text{TeV} \]

dictated by symmetry

\[ \mu^+ + \bar{\nu}_\tau \]

How often does this happen?

\[ \hat{\sigma}_{ij\rightarrow\text{EWSph}}(E_{\text{CM}}) \approx \frac{p}{m_W^2} \theta(E_{\text{CM}}/E_{\text{sph}}) \]

@ parton level

J. Ellis & Sakurai, JHEP(2016)
How often does this happen?

\[
\hat{\delta}_{ij \rightarrow \text{BH}}(E_{\text{CM}}) \approx \pi \left( G_D E_{\text{CM}} \right)^{\frac{2}{D-3}}
\]

@ parton level

\[
G_D = \frac{1}{M_D^{D-2}} \sim \frac{1}{\text{TeV}^{D-2}}
\]

"TeV scale of gravity" in ADD or RS models

SCP, Prog.Part.Nucl.Phys. 67 (2012) 617-650
Common feature: sizable cross section $>\mathcal{O}(10)$ TeV

- Cross section becomes large at around $E_{cm} \sim 10$ TeV

$$\sigma(E_\nu) = \sum_i \int dx f_{i/N}(x, q^2) \hat{\sigma}(\hat{s} = 2mE_\nu x) \sim 1/\text{TeV}^2$$

$E_\nu \sim \mathcal{O}(10^{17} - 10^{21})$ eV

Target nucleon

quark $q$ with parton fraction $x$

PDF

Nucleon’s mass

CR-energy $E_{CM} > 10$ TeV

parton level x-section (NP)

fraction of energy of parton(i) in Nucleon
N-nu cross sections

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UHECR Neutrino flux

From direct observation of UHE neutrinos

Expected neutrino-flux from diffuse gamma-rays

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Event rate spectrum

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Auger 9yrs
Auger 10yrs
IceCube 6yrs

Auger 9yrs (2004–2013)
Auger 10yrs (10yrs, expected)
IceCube 6yrs (2008–2014)

Microscopic BH
$M_B = 1 \text{ TeV}$,
$n = 2–6$

EW Sphaleron,
$E_{\text{Sph}} = 9 \text{ TeV}$,
$p = 0.3$

Auger North

Microscopic BH
$M_B = 2 \text{ TeV}$,
$n = 2–6$

2 TeV gravity

Sphaleron, $p = 0.3$
Features of NP events (i):

Larger charged particle multiplicity

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Longitudinal development of air-shower can be observed by the fluorescence light detector (FD) (in the range of 300-430 nm)

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Features of NP events (iii): broader distribution of the ‘$X_0$’

Probability distribution of the primary interaction point:

$$P(X_0) \propto \exp \left( -\sigma_{\text{int}} N_A A_{\text{atm}}^{-1} X_0 \right)$$

Average atomic mass of atm $\sim 14$

CR-N cross section primary interaction point

$\sigma_{QCD} > \sigma_{NP} \Rightarrow$ NP distribution is broader
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Summary

• UHECRs provide ‘very interesting’ chances of probing NP beyond 10 TeV

• We showed that ‘EW sphaleron’ and ‘Microscopic Blackholes’ are within the reach of future coming observation at Pierre Auger / TA (and IceCube too! stay tuned)

• NP features can be tested by extensive air shower with high multiplicity, more inclined (or deeper), rapidly developing, having broader $X_0$ distribution of interaction points.
(bonus) muon excess

- Auger 9-yrs data suggests that there are ‘muon excess events’ having a larger number of muons compared to the expected.

\[
\langle R_\mu \rangle = \int_0^{X_{\text{max}}} P(X, \sigma_{\text{int}}) R_\mu(X) dX
\]

\[
R_\mu = \frac{N_\mu}{N_{\text{exp}}}
\]

[Pierre Auger collaboration, PRD91(2015) no.3, 032003]
Highly deep air-showers may contribute to the muon excess. (not very plausible)